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Renewable and sustainable approaches for desalination

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ABSTRACT

Freshwater and energy are essential commodities for well being of mankind. Due to increasing population growth on the one hand, and rapid industrialization on the other, today's world is facing unprecedented challenge of meeting the current needs for these two commodities as well as ensuring the needs of future generations. One approach to this global crisis of water and energy supply is to utilize renewable energy sources to produce freshwater from impaired water sources by desalination. Sustainable practices and innovative desalination technologies for water reuse and energy recovery (staging, waste heat utilization, hybridization) have the potential to reduce the stress on the existing water and energy sources with a minimal impact to the environment. This paper discusses existing and emerging desalination technologies and possible combinations of renewable energy sources to drive them and associated desalination costs. It is suggested that a holistic approach of coupling renewable energy sources with technologies for recovery, reuse, and recycle of both energy and water can be a sustainable and environment friendly approach to meet the world's energy and water needs. High capital costs for renewable energy sources for small-scale applications suggest that a hybrid energy source comprising both grid-powered energy and renewable energy will reduce the desalination costs considering present economics of energy.

Contents

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1. Introduction

Freshwater and energy are two inseparable and essential commodities for sustaining human life on earth. Rapid population growth and industrialization, especially in developing countries in the recent past, have placed pressing demands for both freshwater and energy. Supply of freshwater requires energy and unfortunately, many countries in the world that lack freshwater sources, are also deficient in energy sources. While conventional water treatment technologies are adequate to treat surface and ground waters with low dissolved solids [<3000 mg/L] concentration to produce freshwater, desalination technologies are routinely utilized in arid and coastal areas that are deficient in suitable surface water sources but have ample brackish and inexhaustible seawater sources. Although desalination technologies are energy-intensive, they would be appropriate in areas where: there is no alternative (ex: islands), cost of other resources is high (transportation costs), low-cost energy is readily available (ex: middle-east oil rich countries) and high living standards override the cost factor (as in the case of tourism) [1].

Typically, desalination processes are powered by energy derived from combustion of fossil fuels which contribute to acid rain and climate change by releasing greenhouse gases as well as several other harmful emissions. With the Kyoto Protocol coming into effect, several countries have committed to reducing their greenhouse gas emissions. The Kyoto protocol requires global per capita emissions to drop to 0.2–0.7 ton C/cap/year from the current levels of 0.3 in developing countries; 5.5 in USA; and 2.5 in Western Europe [2]. In addition to this, as the limited fossil fuel reserves are being depleted, the need to develop new and alternate energy sources is becoming crucial for energy security and future sustainable development. Known petroleum reserves are estimated to be depleted in less than 50 years at the present rate of consumption [3]. Table 1 presents the world population growth with increased desalination capacity and the oil requirements to produce freshwater through desalination technologies and associated greenhouse gas emissions over the past five decades [4]. Currently, the world established desalination capacity which is only 7.5% of total world's minimum freshwater demand (basis: A minimum of 100 L/cap/day for 6.8 billion current world population) requires 1.42 million tons of oil/day (releases 156 metric-tons of CO_2/day). Now, the question is "can we afford these oil expenses with incurred greenhouse gas emissions and depletion of natural energy sources that threaten the human life?" Therefore, it is necessary to develop alternatives to replace conventional energy sources used in the desalination process with renewable ones and reduce the energy requirements for desalination by developing innovative low-cost, low-energy technologies and process hybridizations. This paper presents possible combinations of renewable energy sources with well-established desalination technologies and the cost requirements of such desalination processes for domestic, small and large-scale applications. Also, the paper discusses alternatives for reducing energy requirements of desalination processes by hybridization and utilization of low-cost, low-grade energy sources and their applications in the desalination industry. Water reuse options and practices to recycle reclaimed water for agricultural and industrial applications are emphasized to relieve the stress on existing natural water resources.

2. Desalination technologies

Currently available desalination technologies can be categorized as follows:

(1) Phase change processes that involve heating the feed (seawater, brackish water or other impaired waters) to "boiling point" at the operating pressure to produce "steam", and condensing the steam in a condenser unit to produce freshwater. Applications of this principle include solar distillation (SD); multi-effect distillation (MED); multi-stage flash distillation (MSF); mechanical vapor compression (MVC) and thermal vapor compression (TVC).
(2) Non-phase change processes that involve separation of dissolved salts from the feed waters by mechanical or chemical/electrical means using a membrane barrier between the feed (seawater or brackish water) and product (potable water). Applications of this principle include electrodialysis (ED) and reverse osmosis (RO).
(3) Hybrid processes involve a combination of phase change and separation techniques (as in the case of non-phase change processes) in a single unit or in sequential steps to produce pure or potable water. Examples include: membrane distillation (MD); reverse osmosis combined with MSF or MED processes.

A comparison based on principle characteristics of the desalination processes is presented in Table 2.

3. Energy and greenhouse gas emissions

Supply of freshwater without any energy input is almost impossible. Even if freshwater is readily accessible under the ground level, energy is required to pump the freshwater from its

Table 1
World population, desalination capacity, oil requirements and greenhouse gas emissions over past five decades.

Year	World population (billions)	World desalination capacity (million m^3/day)	Oil required (million metric tons/day)	GHG emissions[a] (metric tons CO_2/day)
1960	3.1	0.12	0.00	0.36
1970	3.8	0.72	0.02	2.16
1980	4.5	4.4	0.12	13.2
1990	5.3	13	0.36	39
2000	6	23	0.63	69
2008	6.8	52	1.42	156

[a] Basis: 1 m^3 of water generated from an RO plant using fossil fuel (oil) contributes to 3 kg of CO_2 emissions [5].

Table 2
Principal characteristics of different desalination processes.

Characteristic	Type of process		
	Phase change	Non-phase change	Hybrid
Nature	Thermal process: MED, MSF, MVC, TVC (evaporation and condensation)	Pressure/concentration gradient driven: RO (membrane separation, ED (electrochemical separation)	Thermal + membrane: membrane distillation, MSF/RO, MED/RO
Membrane pore size	–	0.1–3.5 nm	0.2–0.6 μm
Feed temperature	60–120 °C	<45 °C	40–80 °C
Cold water stream	May be required	–	20–25 °C
Driving force for separation	Temperature and concentration gradient	Concentration an pressure gradient	Temperature and concentration gradient
Energy	Thermal and mechanical	Mechanical and/or electrical	Thermal and mechanical
Form of energy	Steam, low-grade heat or waste heat and some mechanical energy for pumping	Requires prime quality mechanical/ electrical energy derived from fossil fuels or renewable sources	Low-grade heat sources or renewable energy sources
Product quality	High quality distillate with TDS <20 ppm	Potable water quality TDS <500 ppm	High quality distillate with TDS 20–500 ppm

Table 3
Energy requirements and green house gas emissions for different desalination processes.

Process	Multi-effect solar still (MESS)	Multi-stage distillation (MSF)	Multi-effect distillation (MED)	MVC	MED–TVC	Reverse osmosis	ED
Energy requirements							
Thermal energy (kJ/kg)	1500	250–300	150–220	–	220–240	–	–
Electrical energy (kWh/m^3)	0	3.5–5	1.5–2.5	11–12	1.5–2	5–9	2.6–5.5
GHG emissions (kg CO_2/m^3 H_2O)							
Total electric equivalent (kWh/m^3)	0	15–25	8–201	11–12	21.5–22	5–9	2.6–5.5
Maximum value	0	24	19.2	11.5	21	8.6	5.3

source. Freshwater drawn from the groundwater source requires 0.14–0.24 kWh/m^3 (0.5–0.9 kJ/kg) for a pumping head of 120–200 ft. Treatment of surface waters to potable quality requires 0.36 kWh/m^3 (1.3 kJ/kg) to produce freshwater [6]. The cost of freshwater supply through conventional treatment is less than \$0.25/m^3 [7].

In the case of saline water sources, the minimum theoretical energy required for separating the salts-desalination, to produce freshwater is 0.706 kWh/m^3 [8]. In practice, much higher energy is required by the currently available desalination technologies. In terms of magnitude, about 1 ton of oil is required for every 20 tons of freshwater produced even if all the heat can be extracted from the oil [9]. The oil-to-energy conversion process also results in carbon dioxide contributing to greenhouse effects. Energy requirements for different desalination processes and associated green house gas emissions are summarized in Table 3. The carbon dioxide emissions in Table 3 are estimated based on the assumption that 1 kWh electricity production results in 0.96 kg of CO_2 emissions [10–14].

4. Water and energy sustainability

Desalination processes require large quantities of energy as shown in Table 3. Unfortunately, most large desalination plants around the world are driven by fossil fuels. Continued dependence of desalination processes to produce freshwater on non-renewable energy sources is no longer a sustainable practice due to the risk of depletion of available energy sources and increase of greenhouse gas emissions. It is crucial to develop processes that are renewable and sustainable for freshwater production. The following options are available for managing the water and energy crisis in a sustainable manner:

1. Utilize renewable energy sources,
2. Implement process hybridization,
3. Develop low-cost and energy-efficient technologies,
4. Reuse water.

4.1. Utilizing renewable energy sources

World's prime energy consumption is around 448×10^{15} kJ [15]. Out of which, 84% is derived from non-renewable or depleting energy sources while 16% is derived from renewable energy sources. Renewable energy contributions to total world prime energy consumption are projected up to year 2040 in Table 4. It is reported that known petroleum reserves would be depleted in less than 50 years if the current rate of consumption continues. For a sustainable future, renewable energy applications need to be considered seriously [3]. Moreover, it should be noted that the cost for electricity production from renewable sources is comparable to conventional grid connected electricity generated from fossil fuels as shown in Table 5 [2,16].

Fig. 1 shows potential pathways by which common renewable energy sources can be utilized to drive the different desalination processes [17]. Each pathway involves different technologies, each with its own yield and efficiency. These technologies are discussed next.

Table 4
Renewable energy projections 2040.

	Year			
	2001	2010	2020	2040
Renewable energy sources contribution	14%	17%	24%	48%

Table 5
Comparison of renewable energy costs with fossil fuels.

Source type	Cost (\$/kWh)	Reference
Grid connected electricity (fossil fuel)	0.05–0.09	[2,16]
Geothermal energy	0.07	[16]
Solar powered	0.05–0.09	[2]
Wind energy	0.05	[16]

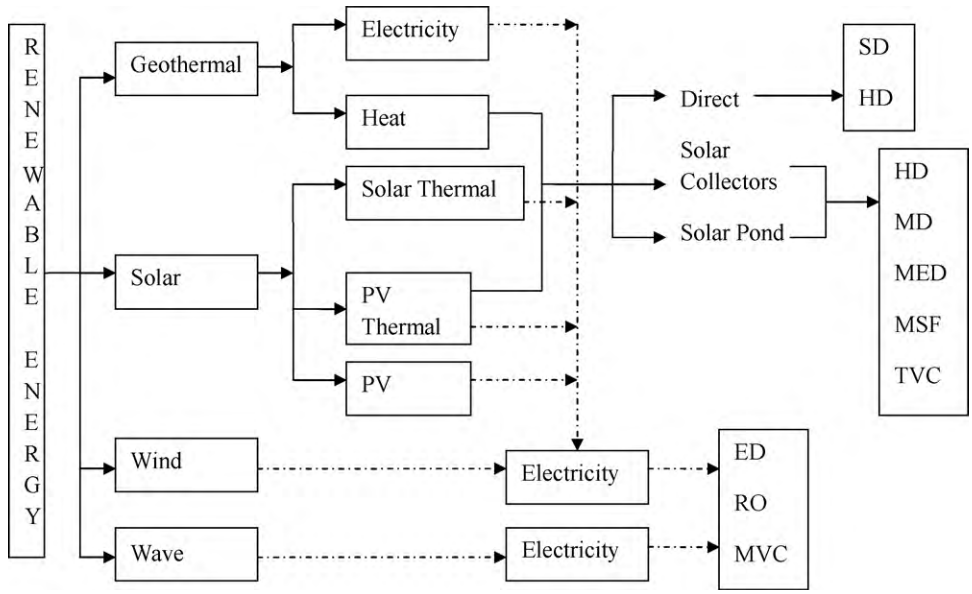

Fig. 1. Possible combinations of renewable energy sources with desalination processes.

4.1.1. Use of solar energy

4.1.1.1. Solar distillation. Direct utilization of solar energy for desalination is by solar stills. Solar energy can be used directly to evaporate water from the sea/brackish and other impaired waters for household or community water supplies. Construction of solar still is simple and is most suitable for areas where the hardware sources are limited. Solar distillation exhibits considerable economic advantage over other present technologies because of its use of free energy and very low operating costs. Distillation with solar energy is a most favorable process for small compact water desalting at geographical locations where there is considerable solar radiation. Another advantage is its simplicity (no moving parts) as it requires low operation and maintenance skills and is highly reliable. Solar stills have been proven to be successful in removal of bacteria, volatile and non-volatile contaminants if proper care were taken to eliminate the contamination of distillate with the feed water [18]. Solar stills can provide necessary daily amount of drinking water for water scarce and drought areas like Africa, Asian countries, etc. [19]. The first large-scale solar-powered desalination plant was installed in Las Salinas, Chile in 1874 with solar still area of 4700 m^2 which was operated for about 40 years [20,21]. However, design problems encountered with solar stills are brine depth, vapor tightness of the enclosure, distillate leakage, methods of thermal insulation, and cover slope, shape and material [22]. Typical still efficiency of 35% with a low productivity of 3–4 L/m^2 and large area requirements are two other factors that prevent large-scale applications of solar stills.

4.1.2. Solar collectors

Solar energy is abundant on the earth and the worldwide consumption of energy is only a 1/16,000 of incoming solar energy [23]. Solar collectors can harvest the solar energy in thermal form which, in turn, can be utilized to drive MSF, MED and MD processes. Table 6 presents the possible combinations of solar collectors with available desalination technologies.

4.1.3. Solar pond

Utilizing solar ponds to drive desalination processes has been demonstrated in many parts of the world. Among many studies, one that is of noteworthy is the work performed by the University of Texas at El Paso (UTEP) on thermal desalination powered by salinity-solar ponds through the support of the U.S. Bureau of Reclamation. Two falling-film, multi-stage flash (MSF) distillation units (Spinflash) have been tested intermittently during the periods of 1987–1988 and 1990–1992, respectively [24]. The pond has a surface area of 3000 m^2 (0.75 acre) and a depth of about 3.25 m (10.7 feet). A multi-effect multi-stage (MEMS) desalination unit was coupled with a solar pond and the performance of the desalination system was measured using different feed water TDS ranging from 1650 to 58,000 ppm. The process operated in the temperature range of 63–80 °C with fresh water production rates between 2.3 and 7.2 m^3/day and the specific energy consumption for the four stage unit varied between 735 and 1455 kJ/kg depending on the process configuration, feed water TDS and cooling stream temperature.

Walton and Lu [25,26] have reported on a salinity gradient solar pond that takes the advantage of the temperature gradient to drive the membrane distillation process. In this system, hot brine was pumped from the bottom of the solar pond and passed through a heat exchanger to supply heat. Cold water from the surface of the solar pond was passed through a heat exchanger to provide cooling. High and low temperatures for system operation were obtained by changing the flow rates for solar pond hot and cold water. Flux per unit area of membrane surface ranges from 0 to 6 L/m^2/h. Flux was measured down to hot side temperatures as low as 13 °C. Flux per unit temperature drop at very low temperatures was only reduced about 50% compared to flux at higher temperatures. This study concluded that operation of MD at such low temperatures may open up thermal energy resources that have not previously been considered for desalination.

Table 6
Possible combinations of solar collectors with desalination technologies.

Type of solar collector	Source of salt water	Desalination process
Direct solar	Seawater, brackish water	Solar stills
Flat panel collectors	Seawater	MED/LTMED
Evacuated tube collectors	Seawater	MSF/TVC
Parabolic trough collectors	Seawater	MED/MEB
Photovoltaic thermal collectors	Seawater, brackish water	MED/LTMED

In another study, a power plant combined with MSF/MED desalination plants used a solar pond. As the power plant operated for only 4 h a day, the exhaust gases released at 550 °C were used partially to drive the desalination process while the rest is used to heat the solar pond. The solar pond stores the rest of the heat and restores it to the desalination plant the rest of the day. Solar pond supplies the seawater feed temperature in the range of 95–120 °C at the first stage. The use of 120 MWe gas turbine coupled to the MED technology permits to reach attractive costs around 0.5 US$/m^3 [27]. Other solar pond driven desalination plants are a MED process of capacity 3000 m^3/day near Dead Sea, MSF process of capacity 60 m^3/day at Margarita de Savoya, Italia and ME-TVC process of capacity 30 m^3/day at University of Ancona, Italy [11,28].

4.1.4. Photovoltaic modules

A PV-electricity system includes PV arrays, DC inverter and battery bank. Today, the maximum efficiency of the PV modules is reported as 14.5%. The advantage of employing a battery bank in the PV–RO system is to provide constant energy flow during night time and to buffer the variations in the electricity production due to passing clouds and rainy days.

The potential combination of solar photovoltaic (PV) power with reverse osmosis has generated growing interest because of inherent simplicity and elegance of both technologies. The compatibility of reverse osmosis with solar photovoltaic power and other renewable energy forms has been greatly enhanced by the advent of efficient and reliable energy recovery pumps, which recycle the hydraulic energy of the reject brine to assist pumping the feed water [29]. Many installations have been demonstrated throughout the world especially in rural areas for small desalination capacities in the range of 1–5 m^3/day based on electrodialysis and reverse-osmosis processes [30–37]. The advantages of photovoltaic energy over conventional diesel generator are reported as: environmental-friendly, no air or sound pollution, minimum maintenance and constant power generation efficiency throughout life time [38].

Although RO desalination is simple with use of PV modules, the rechargeable batteries used to store the produced electricity require high capital costs and periodic maintenance. Problems encountered with batteries are: premature battery failure, leaks in the lead-acid batteries and battery efficiency [39]. Typical battery life time in Europe is between 3 and 8 years, but in hot countries the battery life is reduced to 2-6 years due to internal corrosion at high temperatures. The battery efficiency in the market is about 75–80%. This indicates that around 20–25% larger PV array area is required [36]. On the other side, it is encouraging to note that the cost of PV modules over past two decades has decreased by 6 times, 22 Euro/Wp in 1978 to 3.5 Euro/Wp in 2000 and the installed capacity has increased from less than 100 MW to 2000 MW for the same period [39,40] which makes the application of PV modules an attractive option in many parts of the world where the conventional energy costs are high [2].

Options to reduce capital and operating costs in the PV–RO system include:

- Building battery-less PV generation system,
- Adopting variable speed positive displacement energy recovery pumps,
- Develop hybrid processes for lower specific energy consumption (PV–RO/NF/UF).

Battery-less PV–RO and PV–ED desalination systems have been studied for small-scale applications with desalination capacities 1–10 m^3/day [41,42,43]. A small desalination capacity of 3.9 m^3/day was tested with specific energy consumption of 3.5 kWh/m^3. Schafer et al. studied a hybrid membrane combination (UF/RO–NF) system powered by Photovoltaic system. The UF membrane system removed the suspended particulates, bacteria and viruses, pre-treating the feed water for reverse osmosis or nanofiltration. The specific energy consumption for this hybrid process was reported as 2–8 kWh/m^3 [37]. In another study, the minimum specific energy consumption for reverse-osmosis powered by PV electric system is reported in the range 1.1–1.8 kWh/m^3 depending on the quality of the feed source and the efficiency of the membrane technology [35].

4.1.5. PV thermal collectors

The advantage of PV/thermal collectors is that they produce electricity and thermal energy simultaneously. Collector fluid that circulates through the PV thermal collectors achieves two purposes: (1) it cools the surface of the PV modules which increases the electrical conversion efficiency of the PV module, (2) by doing so, reasonably high-temperature fluid suitable for various applications is prepared. Thus the PV thermal systems are able to supply both thermal and electrical energies simultaneously.

Gude et al. have studied through simulations a combined desalination system with PV/thermal collectors to produce electricity and freshwater at reasonable energy expenses. The results showed that 150–200 L/day of freshwater can be produced with a 25 m^2 area of photovoltaic/thermal collectors while supplying 21 kWh/day of electricity for household needs. There is growing interest in the zero energy homes especially in the eastern states of USA which may provide the benefit of generating household electricity needs along with freshwater production [44].

A miniature concentrator PV/thermal system is being developed by Kribus [45], producing about 140–180 W of electricity and an additional 400–500 W of thermal energy. This system can operate over a wide range of temperatures, and provide thermal energy not only for water heating, but also for cooling, desalination, and industrial process heat. Hot water temperatures as high as 90 °C can be gained from this collector. An analysis of the system performance has shown that at elevated temperatures, the electrical efficiency is somewhat lower, but most of the lost electricity is recovered as thermal energy. The total cost was normalized by the net produced power (electricity only) to yield the cost of $2.5 per peak electric Watt. This is a very competitive cost, which is below the stated EU medium-range target of $3 Wp. The usual market price for PV systems is in the range of $6–8 Wp, depending on system size.

4.1.6. Use of geothermal energy

Geothermal energy is a proven technology for electricity production, although not spread out commercially.

Geothermal energy can be used for desalination due to following advantages:

1. Geothermal energy provides a stable and reliable heat supply ensuring the stability of thermal desalination as well as reverse osmosis.
2. Geothermal production technology (extraction of hot water from underground aquifers) is mature.
3. Typical geothermal source temperatures are in the range of 70–90 °C, which is ideal for low-temperature MED desalination.
4. Geothermal desalination is cost effective, and simultaneous electricity production is possible.
5. Geothermal desalination is environmental-friendly, as only renewable energy is used with no emissions of air pollutants and greenhouse gasses.
6. Geothermal desalination saves imported fossil fuels which can be used for other purposes.

High-temperature geothermal energy sources are suitable for electricity production while low-temperature sources can be used for desalination. Hot brines may be fed directly to distillation plants. The advantage with geothermal sources is that energy output is generally invariant with less intermittence problems making them ideal for thermal desalination processes. Another possible advantage with geothermal waters is; the feedwater itself can be replaced by the geothermal waters, in other words, the geothermal water can serve both as feed and heat transfer medium for desalination.

Karystsas has described a case study of a low enthalpy geothermal energy driven seawater desalination plant on the Milos island in Greece [46]. The proposed design consists of coupling MED units to a geothermal groundwater source with temperatures ranging from 75 °C to 90 °C. The study showed that the exploitation of the low enthalpy geothermal energy would help save the equivalent of 5000 TOE/year for a proposed plant capacity of 600–800 m^3/day of fresh water. Even in the case of limited geothermal energy, thermal desalination processes such as MED, thermal vapor compression (TVC), single-stage flash distillation (SF) and MSF can benefit greatly when coupled to geothermal sources by economizing considerable amounts of energy needed for pre-heating.

Bouchekima [47] has analyzed the performance of solar still in which the feed water is brackish underground geothermal water. Bourouni has demonstrated an aero-evapo-condensation process which was found to be promosing for cooling as well as for desalting geothermal water. In this study, a geothermal spring with a water temperature of about 70 °C was used [48,49]. Kamal [50] had shown that enhancement of feed water temperature for seawater reverse-osmosis plants located in southern California induced a substantial reduction in the cost of potable water. The membrane productivity increase is about 2–3% per 1 °C increase of the feeding temperature. Most of the membranes commercialized for RO desalination processes can tolerate temperatures up to 40 °C. However, few membrane suppliers offer new membranes for high-temperature applications. For example, Backpulseable™ membranes (polypropylene tubular membranes) can tolerate temperatures up to 60 °C. It is important to note that an increase of the feeding water of the RO desalination plant of Gabes to 40 °C (temperature tolerance of most commercialized membranes) will increase its productivity of about 20–30% [51].

Disadvantages: Geothermal brines in addition have the disadvantage of high salt concentration that create in general operational problems, hard scale formation and concentrated brine disposal, if not near the sea [16].

4.1.7. Use of wind energy

Almost all countries in the world have the wind energy sources in some areas. Wind conditions on mountain stations, coastal areas, and islands are favorable for wind-powered desalination systems. For the operation of a wind-powered desalination plant, it is important to have a suitable process that is insensitive to repeated start-up and shutdown cycles caused by sometimes rapidly changing wind conditions. Even though there are several desalination processes with varying degrees of technological maturity, only a few can utilize the electrical energy from a wind turbine and that are technologically ready to be employed; namely reverse-osmosis and mechanical vapor compression.

Mechanical vapor compression (MVC) process is more tolerant of intermittent operation than RO but is not traditionally used with a variable power supply. Several research installations have been tested to determine the feasibility of reverse-osmosis and vapor compression units with combination of wind-power [52,53]. However, two autonomous wind-driven MVC desalination plants have been built that operate with variable power. In both plants a variable speed compressor and a resistive heating element in the brine tank allow a variable amount of power to be absorbed by the unit [54,55]. The plant on Borkum Island uses a 60 kW wind turbine and an MVC unit with a 4–36 kW compressor and a 0–15 kW resistive heater. It produces distillate at 0.3–2 m^3/h with a specific consumption of 16–20 kWh/m^3 [56,57]. Another wind-powered MVC desalination plant was demonstrated on the Island of Rugen, in Baltic Sea with a capacity of 360 m^3/day [54]. The wind energy production capacity for this application was 300 kW. The distillate production varied between 2 and 15 m^3/h depending on the wind speed conditions.

Advantages with this system were:

- low-energy demand due to efficient heat recovery,
- variable rotor speed for higher energy gains complete utilization of wind power for desalination,
- low process temperatures,
- only wind energy is needed for operation.

The economics of a wind-powered desalination system differ from conventional plant economics since it is almost entirely based on the fixed costs of the system. There are no fuel costs for the system since the wind turbine, being largely a capital expenditure, replaces the fuel costs of the system. Therefore, energy efficiency is not the main determining factor, but rather the economics of the process.

Due to intermittence in the production of wind energy, suitable combinations of other renewable energy sources can be employed to provide smooth operating conditions. Wind Generator/Photovoltaic energy combination can drive the desalination process round the clock with a battery bank system [58,59]. Combining these two renewable energy sources with desalination may have several inherent advantages. However, maintenance of the battery bank system can be a major concern. Another factor of interest is the storage capacity of freshwater. Water is an excellent storage medium and can be stored in vast quantities for extended periods of time. Therefore, it is possible to produce water and store it when the power supply is available, for use when the power supply drops. Therefore, it is possible to produce water when the power supply is available and store water when it is not. This alleviates the need for expensive back-up systems in the areas which have desalination need with good wind resources.

4.1.8. Use of wave energy

Wave energy is ideal for desalination in the coastal areas where both energy and seawater are readily available. Wave-powered technology to produce electricity has an experimental history of at least 30 years. Wave energy stands out from other types of renewable energy resource, not only in terms of the intensity of the primary resource, but also in terms of the conversion efficiencies obtainable in theory as well as in practice. For comparison, efficiency of solar energy conversion is commonly held to be limited to 86.7%. This theoretical efficiency is based, however, on assumptions about devices constructed from numerous layers. In contrast, there appears to be no theoretical reason why wave energy converters cannot reach 100% efficiency. Wave tank devices yielding efficiencies over 80% have been demonstrated in practice.

While six existing wave energy technologies can potentially power reverse-osmosis and vapor compression, buoy and oscillating water column are the two main technologies that are successful at full-scale operation [60]. The first reported wave-powered technology was the DELBUOY, which used oscillating buoys to drive piston pumps anchored to the seabed. These pumps fed seawater to submerged RO modules. DelBuoy consisted of a simple linear reciprocating pump driven by the motion of the waves and connected via nonreturn valves that produce flow in

one direction to a reverse-osmosis membrane; the unit produced an average of 2 m^3/day. Although the system worked successfully for 18 months, the specific energy consumption, though not given, would have been high due to the absence of energy recovery technology and the low recovery-ratio that allowed the system to operate without the need for chemical additives.

An autonomous wave-powered desalination plant was first demonstrated in Kerala, India [61]. 10 m^3/day reverse-osmosis desalination plant was based on Oscillating Water Column (OWC) principle. This arrangement encloses a column of air on top of column of water. The wave action causes the water column to rise and fall, which alternately compresses and depressurizes the air column. Energy is extracted from the system and used to generate electricity by allowing the trapped air to flow through a turbine. This electricity was used to drive the reverse-osmosis unit at a feed flow rate of 30–40 L/min and the product water recovery is 10–15 L/min. This is an indirect process, similar to the schemes that involve other renewable energy sources, with one main advantage when compared to ones that use these other resources, which is the distance to the seawater. In another study [62], the potential for an autonomous wave-powered desalination by reverse-osmosis (RO) plant utilizing a pressure exchanger-intensifier for energy recovery was considered. A numerical model of the RO plant showed that a specific energy consumption of less than 2.0 kW h/m^3 over a wide range of seawater feed conditions, making it particularly suitable for use with a variable power source such as wave energy. For a typical sea-state the specific hydraulic energy consumption of the desalination plant is estimated to be 1.85 kWh/m^3 while maintaining a recovery-ratio of less than 25–35% to avoid the need for chemical pre-treatment to eliminate scaling problems. A techno-economic model developed for this plant indicated that fresh water can be produced for as little as $0.8/$m^3$ [63].

Waves will generally be available where seawater is desalinated. But the harnessing of wave energy is, as with other forms of renewable energy, expensive in terms of capital plant and the effort needed to develop the technology. It may well require the intervention of governments or international bodies. The failure to exploit the wave resource probably stems from the fact that the nations having the most abundant wave resources, such as the UK and Norway, have also been endowed with their own indigenous resources of oil and hydroelectricity. This has given them limited incentive to develop and exploit novel renewable technologies. Another factor is the lack of niche applications that would have allowed the wave energy market and industry to develop gradually in size. Renewable energy technologies such as wind turbines, wind pumps and solar panels of various kinds have for decades been used in applications such as remote dwellings, radio repeaters and satellites. These gradually evolved into the large-scale applications of today.

4.2. Process hybridization

Conventional desalination systems are both energy and cost intensive if they were to operate stand-alone. Cogeneration of electricity and desalination for freshwater production is an accepted principle in many countries [64]. Cogeneration has been widely practiced to generate power and desalinated water at reasonable cost. Coupling the power plants with MSF process is very well considered in many parts of the world due to its suitability for large-scale application [65]. Desalination in Gulf States has first begun with a MSF unit of capacity 4500 m^3/day in Kuwait. The specific energy requirement for a MSF process is 290 kJ/kg if it is not connected to a power plant, when it is connected to a power plant; the specific energy requirement is only 160 kJ/kg [11].

4.2.1. Coupling MSF with RO process

MSF desalination technology has been proved to be a robust technology for desalination. Today, 60% of the desalination capacity is provided by MSF plants throughout the world and a share of up to 80% in the Middle East countries [66]. However, RO desalination has been steadily gaining ground as a viable technology with certain advantages and technical merits. MSF and RO are both suitable for side-by side coexistence and for full integration in what is known as MSF–RO hybrid desalination systems.

Integration of MSF and RO in certain hybrid desalination process configurations can be beneficial both technically and economically. MSF–RO, NF/SWRO/MSF hybrid schemes with different design configurations have been studied both theoretically and experimentally [67–70]. The most feasible hybrid configuration is MSF–RO hybrid configuration is the simplest of its kind. It can be easily implemented in existing MSF plants. It utilizes the cooling seawater reject from the MSF heat rejection section to feed the RO desalination system [71–73]. Coupling of the heat source to the MSF desalination system can be obtained from the extracted or exhaust steam of the extraction-condensing or backpressure turbines, respectively. Coupling of the electrical source to the RO desalination system can be obtained from the generated electricity of the local electric network. Technical and economic advantages of the corresponding schemes mentioned above, remain in force. However, owing to MSF–RO hybridization, some of these benefits include:

- Greater flexibility in dual-purpose power-water cogeneration. Maximum operational flexibility and maximum rapid response to load variations and alternation between different modes of operation, particularly in the combined power cycle coupling scheme. This is a result of the possible rapid start-up and shutdown of both the gas turbine and RO systems [74].
- Increased product water recovery (a 40–45% increase in water production related to pre-heating of feed water to the RO plant up to 35 °C. Plants situated in Mediterranean countries can improve their efficiency, particularly in winter operation when the sea temperature rarely exceeds 20–22 °C), lower product water costs.
- Lower specific energy consumption for water production [75].
- Utilization of common seawater intake systems with lower capacities.
- Lower chemical consumption and RO membrane replacement rates and prolonged life cycle of these RO membranes [72,76].

The reductions in the product water costs under hybrid MSF–RO desalination systems are guaranteed and significant due to savings in both capital investment and operating costs owing to the elimination of redundant auxiliary systems and the utilization of common facilities for power, MSF and RO systems.

4.2.2. Integrating membrane distillation (MD) with other desalination processes

Using MD as an end process for MSF or ME, to utilize hot reject brine from MSF or ME as the feed solution is not studied yet. Investigation of integrating MD with RO, however, has been carried out by Drioli. The reject brine from RO is used as the feed solution for MD. Because MD is much less sensitive to concentration, more fresh water can be produced and the RO brine volume can be furthermore reduced in the MD unit. The reduction of the quantity of brine produced leads to a lower environmental impact. Their cost analysis assuming a MD plant installed at a cost of $116/$m^2$ is as follows: Only RO – $1.25/$m^3$; only MD – $1.32/$m^3$; and RO + MD – $1.25/$m^3$. It shows that a combined RO + MD plant produced more than twice as much water as the stand-alone RO plant at the

same water cost. The stand-alone MD plant produced as much water as the RO + MD plant, but at a water cost about 5% higher [77,78].

4.2.3. Hybrid membrane process

A hybrid membrane configuration incorporated an ultrafiltration (UF) module for removing particulates, bacteria and viruses, while a reverse-osmosis (RO) or nanofiltration (NF) membrane retains the salts. The concepts of water and energy recovery are implemented in this design. Field trials, performed in White Cliffs (New South Wales), demonstrated that clean drinking water could be produced from a variety of feed waters, including high salinity (3500 mg/L) bore water and high turbidity (200 NTU) dam water. The specific energy consumption ranged from 2 to 8 kW h/m^3 of disinfected and desalinated drinking water, depending on the salinity of the feed water and the system operating conditions [37]. Different combinations of desalination processes, both thermal and membrane, are considered for energy recovery and fuel savings, which are summarized in Table 7 [79].

4.3. Low-cost and low-energy desalination technologies

Up to 30% of desalination cost is due to the energy requirement for the production of freshwater [80–82]. Combining desalination technologies with available low-grade waste heat sources is beneficial and can improve the economics of the combined processes. Low-grade heat sources with temperatures as low as 60 °C can be effectively and economically utilized. Such low heat sources could be available from almost any conventional or nuclear power system and sometimes can be obtained free of cost.

Low-temperature desalination has the following benefits [83,84]:

- *Low corrosion rates*: The reduced corrosiveness of seawater at low operating temperature and vacuum conditions permits safe and economic use of corrosion-proof plastic materials and coatings both for Piping and for vessel linings, as well as the use of aluminum for heat transfer tubing and vessel internals. Low maintenance and extended plant life (exceeding 25 years) result from the combination of the low corrosion rates and the use of a mild anti-scalant.
- *Flexibility*: LTD plants have short start-up periods with little time loss for heating up. Plants have excellent load following capabilities allowing for production to closely match both water demand and energy supply.
- *Thermodynamic efficiency*: The use of generous heat transfer surfaces results in a reduction of heat fluxes and temperature differentials and therefore in an increase of thermal efficiencies. As a result, the evaporative condensers operate with overall temperature differentials, including thermal driving forces, boiling point elevations and non-condensable gases and fouling factors, as low as 2–2.5 °C. Thermodynamic advantages of low-temperature desalination are discussed in detail by Gude et al. [84].
- *Minimal scaling rates*: The operating temperatures are well below the saturation limits of problematic scalants found in sea and most ground waters. Scale is reduced to an insignificant level, enabling plants to operate for long periods – 5 years in some cases – between cleanings. Low-cost polyelectrolyte feed pretreatment is adequate. Descaling is a simple procedure, consisting of mild acid recirculation, using the plant's own recirculation pumps.
- *High-purity distillate*: An additional advantage is the high purity of the product water (usually less than 20 ppm and as low as 2–5 ppm for special applications). This allows the water to be used directly for industrial processes such as in refineries, power stations, breweries etc., where boiler water quality is required or in municipal installations to reduce the production costs further by blending the high-purity distillate with local brackish or poor-quality water and satisfy the potable water standards.
- *Reliability*: Experienced engineering, rugged construction and proven equipment combined with extremely low corrosion and scaling rates result in minimal maintenance and lead to annual plant availability in excess of 95%.
- *Low-energy costs*: The low-temperature operation in dual-purpose application enables the use of low-grade, low-cost sources of heat, which would otherwise be lost through being released into the environment in the form of stack gases, cooling water streams or low pressure exhaust steam. The motive energy cost component for the desalination process is reduced to a minimum, and consequently the water production costs are lower than any other seawater desalination system.

4.3.1. Utilization of low-grade waste heat sources

In diesel-cogeneration installations, the MED draws the motive energy for desalination from the waste heat recovered from the exhaust gases and the jacket water cooling system of a diesel generator power station. This virtually free energy brings the operating costs of the desalination unit down to a minimum and the thermal efficiency of the diesel power station up from approximately 40% to over 80%. Back pressure steam from the power plants can be coupled with MED process. Low-temperature MED (LTMED) systems can be combined with the waste heat rejected by condensers at about 60 °C [83,85].

A low-temperature desalination process which can utilize the waste heat released from the condenser of a domestic air-conditioning system has been studied through theoretical simulations [86,87]. The study incorporates a thermal energy storage (TES) unit where the TES is maintained at the design temperature by a solar-powered absorption refrigeration system (ARS) augmented by an electric heater. Results of this feasibility study show that the heat rejected by an ARS of cooling capacity of 3.25 kW (0.975 tons of refrigeration) along with an additional energy input of 208 kJ/kg of desalinated water is adequate to produce desalinated water at an average rate of 4.5 kg/h. The solar panel area required for this application was 25 m^2. An experimental study powered by grid proved that seawater desalination is achievable at feed temperatures as low as 40 °C [84]. Slesarenko

Table 7
Energy and fuel savings through hybridization.

Hybrid process	Capacity (m^3/day)	Energy (kWh/m^3)	Fuel savings (tons/year)
SWRO/MED (LT-TVC)	14,300	9.58	4937
SWRO/BPT/MED (LT-TVC)	14,800	9.23	5319
SWRO/BPT/SWRO	14,700	9.34	4162
MVC/MED (LT-TVC)	19,000	7.27	11,094
SWRO	11,000	12.5	

SWRO: seawater reverse osmosis; MED: multi-effect distillation; BPT: backpressure turbine; MVC: mechanical vapor compression; LT-TVC: low-temperature thermal vapor compression.

has presented a combined system in which heat pumps can utilize the heat rejected by the power plants to drive the desalination processes effectively without any losses of heat to the environment [85].

4.3.2. Low-temperature desalination systems

Low-temperature streams with temperature at only 8 °C above the ambient seawater temperature can be utilized for desalination. An Italian desalination plant constructed in 1990s is still in operation providing high quality distillate for process applications with production cost of 0.6 $/m^3$ of desalinated water [88]. Recently a low-temperature thermal desalination (LTTD) unit has been developed by National Institute of Ocean Technology, India which exploits the temperature differences available in surface level and deep sea level temperatures to achieve flash distillation under vacuum. Surface level seawater temperatures are usually around 28–30 °C and the deep seawater temperatures are around 7–15 °C. The former stream serves as feed and is exposed to vacuum in the flash distillation unit while the water vapor generated is condensed by the later stream to produce freshwater. The specific energy consumption for 1 m^3 of freshwater is 8 kWh with production costs around 0.65 $/m^3$ [89–90]. Another approach to utilize ambient energy harvested by low-cost building roof materials has been studied by Virk et al. 26 m^2 area of roof delivered constant energy flow of 10 kW to produce 0.32 m^3/day [91].

4.4. Water reuse

In most parts of the world, the conventional water supplies are diminishing and the need for water reuse is inevitable. As demand for existing resources in water-scarce areas become greater, water reuse gains more potential in certain uses and if used, releases natural sources of water for potable supplies. Need for water reuse could be mainly due to following reasons: population growth, limited land space or drought conditions (depleting natural water resources such as rivers, lakes and aquifers). Recycled water can be used for a wide range of applications most commonly for non-potable purposes. Uses can include irrigation, for example agricultural, horticultural and green spaces; environmental purposes; and domestic non-potable uses such as third pipe systems. These uses are often employed to reduce the pressures on other existing water sources or to provide a water source where a suitable one does not already exist.

Wastewater sources for water reuse can be of four types:

- Municipal wastewater,
- Industrial wastewater,
- Agricultural wastewater,
- Grey water (wastewater from clothes washers, bath tubs, showers and sinks).

Reclaimed water reuse for other potable uses has been very well accepted in many parts of Australia [92]. Grey water reuse is widely practiced in United States, Europe and many other countries in Middle East. United States has a long history of water reuse beginning in 1912 for watering the lawns in California. USEPA has set the guidelines for the water reuse practice based on the type of use. The quality of the product water for reuse differs for various applications such as: urban reuse, agricultural reuse, recreational impoundments, construction uses, cooling uses, groundwater recharge of potable aquifers and augmentation of surface suppliers [93]. Table 8 shows the percentage of water reuse in Middle East countries. Kuwait and Qatar take lead in water reuse program with more than 10% of reclaimed water out of total water supply [94].

Table 8
Water reuse practices in Middle Eastern countries.

Country	Total water supply ($m^3 \times 10^6$/year)	%Water reuse
UAE	576.8	0.14
Bahrain	170	0.29
Oman	423.6	2.03
KSA	4570	4.75
Qatar	200	10
Kuwait	767	10.43

Combining strategies of water reuse and desalination technologies makes it possible to convert wastewater into high quality water that suits various industrial applications. Technologies for water reuse and desalination have much in common. Feed source for both is an impaired water source whether it is seawater or produced water. The technology that is used most widely for water reuse or desalination is based on membranes for several reasons. Desalination by reverse-osmosis membranes combined with the use of conventional pre-treatment units or modern pre-treatment technologies are now well-established methods of wastewater desalination techniques [94,95]. Microbial retention is a major concern in water reclamation which can be achieved by microfiltration (MF) and ultrafiltration (UF). MF and UF are employed as preferred pre-treatment processes for nanofiltration (NF) or reverse osmosis (RO), i.e. the quaternary treatment step which can produce drinking or ultrapure process water quality. This dual membrane treatment concept plays now a major role in water reclamation schemes that are aimed at advanced levels of purification. Applications include several aquifer recharge projects (one even for indirect potable reuse), dual water systems in households and industrial process water, or for mixed urban and agricultural uses.

Water production costs to treat the effluent from the conventional activated sludge followed by membrane bioreactors through RO process have been compared with the seawater process. The total life cycle costs for the produced water from secondary effluent (RO) is two times cheaper than the traditional desalination process from seawater (SWRO). The advantages of the reclaimed process over the traditional seawater process are the following: no pre-treatment required, higher recovery with higher flux rates at lower operating pressures (energy savings) and longer membrane life [96].

5. Selection criteria for a desalination process

Selection of appropriate desalination process requires complete analysis of the plant from start to end. Irrespective of the production volume, the following factors need to be considered when selecting a desalination process:

1. Need for desalination:
   a. Capacity
   b. Quality
2. Energy source, infrastructure, hardware:
   a. Solar
   b. Wind
   c. Wave
   d. Geothermal
3. Feed water source:
   a. Seawater
   b. Brackish water
   c. Produced water (wastewater reuse)
4. Process:
   a. Type of process

b. Specific energy requirements
c. Characteristics
5. Economic feasibility:
a. Financing
b. Capital costs
c. Operating costs
6. Environment:
a. Brine disposal
b. Use of chemicals

Consideration factors are discussed in detail by Adrianne et al. [97].

6. Desalination cost estimations

Estimating the capital and production costs of desalination systems is very difficult due to following reasons: Variable energy, material and labor costs by geographic areas, the type of desalination process/design/size, salinity of feed water source and financing packages [6]. Many researchers have presented actual capital and operating costs for different desalination systems in many parts of the world. Expressing the desalination costs in a common currency provides a reference to the allowable costs in plant construction and operation for a given desalination capacity. Desalination cost per unit produced water for different desalination processes coupled with renewable energy sources and different feed sources are summarized in Table 9. Capital investment and desalination costs for different desalination processes powered by conventional energy in the capacity range of 200–40,000 m^3/day are presented in Table 10. The high range of desalination cost is due to the fact that the small-scale applications powered by renewable energies as well as conventional energies require high capital costs [98–100]. The capital costs as well as operation and maintenance costs can be reduced if a hybrid energy source comprising both fossil fuel energy and renewable energy is considered [101]. Such hybrid energy source can reduce the production cost of desalinated water along with lower emissions of CO_2 and lower electricity consumptions [100]. Though renewable energy sources are attractive solutions to combat the effect of greenhouse gases released from fossil fuels, their applications are limited by source nature, capital costs and design problems [102]. A breakdown of desalination processes driven by renewable energy sources worldwide is as follows: reverse-osmosis 62%, electrodialysis 5%, MSF 10%, MED 10% VC 5% and others 4%, out of which 43% of the desalination processes are powered by solar PV energy, 27% by solar thermal, 20% by wind and10% by hybrid combinations. Thus, one can conclude that PV and wind energy sources in combination with RO and VC are suitable for desalination applications. Although photovoltaic energy and wind energy are promising alternative energy sources to power desalination processes, the high cost of photovoltaic modules and the intermittent/unpredictable nature of wind energy are the main barriers for their applications. For desalination processes powered by renewable energy sources with capacities in the range 2–24 m^3, the desalination cost could vary between 1.5 and 18.75 $/$m^3$. For instance: solar collectors, when used for small-scale applications, the desalination cost can be as high as 4.3–10 $/$m^3$ [98]. Based on the above, renewable energy applications for very

Table 9
Desalinated water costs for various combinations of desalination processes powered by renewable energy sources [98,103].

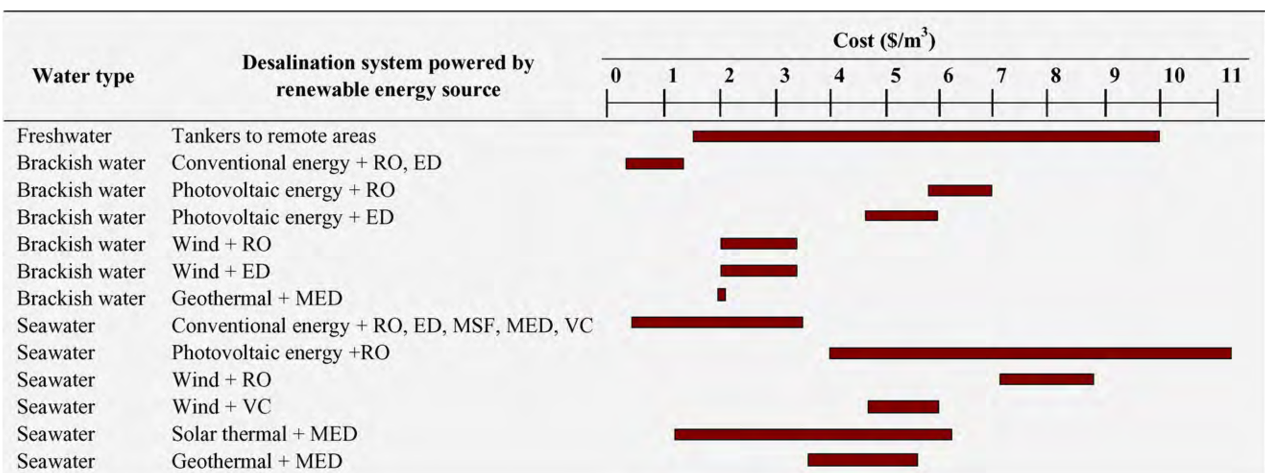

Table 10
Investment and production costs for desalination processes with capacities in the range 200–40,000 m^3/day [104,105].

Desalination process	Capacity (m^3/day)													
	200		600		1200		2000		3000		20,000		30,000–40,000	
	Cost/unit ($/$m^3$)	Investment (M$)	Cost/unit ($/$m^3$)	Investment (M$)	Cost/unit ($/$m^3$)	Investment (M$)	Cost/unit ($/$m^3$)	Investment (M$)	Cost/unit ($/$m^3$)	Investment (M$)	Cost/unit ($/$m^3$)	Investment (M$)	Cost/unit ($/$m^3$)	Investment (M$)
MVC	3.8	0.75	2.65	1.7	2.25 3.22	3.2 1.58								
RO	3.25	0.5	2.35	1.1	2.15	2	2	3	1.85	4.2				
MED					1.6	2.3	0.825	3.25	0.65	4.85	1.24	35	1.31 1.08	67 70
MED–TVC	3.3	0.5	2.25	1	1.85	1.65	1.8	2.5	1.7	3.3	1.55	35		

Table 11
Desalination capacities based on freshwater requirement.

Type of facility	Capacity (m^3/day)
Domestic (single/double family dwellings or luxury house)	<1
Small scale (small/large hotels, small towns/villages/rural places)	1–1000
Large scale (cities/towns with lower energy costs, industrial sectors)	1000–100,000

small-scale applications are still viable in remote areas where the transportation costs to supply freshwater are higher (see Table 9). The value for freshwater increases especially in areas where the scarcity for both water and energy is highly pronounced. Installing an autonomous renewable energy driven desalination process will not only ensure the supply of freshwater but also will bring down the cost for freshwater production. However, the desalination cost factor can be counterbalanced by the environmental benefits offered by renewable energy sources.

Additionally, in this work an effort has been made to separate the desalination systems into three types of applications to help one estimate the possible production costs for desalination. The three types of applications are: domestic, small-scale and large-scale systems. According to World Health Organization (WHO), 20 L/day per capita is sufficient to provide basic hygiene needs [106]. However, it is reported that the global average domestic water usage is around 55 L/day excluding agricultural and industrial use [99].

A domestic desalination system can be considered for the freshwater needs of a single or two family dwellings or luxury house. A small-scale desalination system can be considered for small populations in rural areas, small villages up to 10,000 people for freshwater needs only. A large-scale desalination system can be considered for cities and towns where the electricity costs are reasonable. These desalination systems can provide the freshwater for industrial applications as well. Table 11 shows the desalination capacities for the above three categories and Table 12 presents representative production costs for different desalination capacities.

From Table 12, it can be noted that membrane processes are used for small to medium size desalination capacities and thermal processes for large size desalination capacities. For very small applications with desalination capacities <100 m^3/day, the desalination cost is very high in both cases (conventional and

Table 12
Desalination costs for different desalination processes based on capacities.

Desalination process	Capacity (m^3/day)	Energy source	Energy cost ($/kWh)	Desalinated water cost ($/$m^3$)	Reference
Domestic applications					
Solar still	0.006	Solar		12.53	[99]
Solar still	0.009	Solar		10	[99]
Solar still	0.8	Solar		12.5	[99]
Solar still	1	Solar		12	[107]
MESS	1	Solar		50	[13]
PV–RO	1	Solar		12.05	[107]
PV–RO	1	Solar		3.73	[110]
MD	0.1	Solar		15	[107]
MD	0.5	Solar		18	[107]
MD	1	Geothermal		130	[13]
MSF	1	Solar		2.84	[107]
Solar still	5	Solar		0.52–2.99	[108]
ED	5	Electric		5	[107]
RO	10	Electric		4	[107]
MED	<100	Conventional		2.5–10	[98]
MVC	375	Conventional		2.9–3.8	[109]
Small-scale applications					
Reverse osmosis	250	Diesel generators	0.07	3.21	[82]
Reverse osmosis	300	Diesel generators	0.06	1.82	[2]
Reverse osmosis	350	Diesel generators	0.06	1.36	[2]
Reverse osmosis	500	Diesel generators	0.07	2.94	[82]
Reverse osmosis	500	Diesel generators	0.06	1.42	[112]
Reverse osmosis	500	Diesel generators	0.06	1.25	[112]
Reverse osmosis	500	Diesel generators	0.06	2.57	[111]
Reverse osmosis	600	Diesel generators	0.06	2.95	[111]
MVC	1000	Conventional		1.51	[113]
MVC	1000–1200	Wind		2–2.6	[11]
MVC	1200	Conventional		3.22	[105]
Vapor compression	3000	Conventional		0.7	[98]
MFD	10,000	Conventional		0.88	[58]
MED	12,000–55,000	Conventional		0.95–1.95	[59]
MSF	20,000	Natural gas		2.02	[107]
Large-scale applications					
Dual-purpose MSF	20,000	Natural gas/steam	0.0001	0.08	[99]
Reverse osmosis	2000	Diesel generator	0.06	2.23	[2]
Reverse osmosis	5000	Diesel generators	0.06	1.54	[2]
Reverse osmosis	10,000	Diesel generators	0.05	1.18	[2]
Reverse osmosis	20,000	Diesel generators	0.05	1.04	[2]
Reverse osmosis	50,000	Diesel generators		0.86	[2]
Reverse osmosis	95,000	Conventional		0.83	[6]
Reverse osmosis	100,000	Conventional		0.43	[6]
Reverse osmosis	$100–320 \times 10^3$	Conventional		0.45–0.66	[59]
MED	$91–320 \times 10^3$	Conventional		0.52–1.01	[98]
MSF	$23–528 \times 10^3$	Conventional		0.52–1.75	[98]

renewable energy). The desalination cost is lower for higher desalination capacities whether they are powered by conventional energy or renewable energy. However, considering high capital costs required for renewable energy sources for large-scale applications, thermal processes may be considered where the cost for thermal energy is attractive as in the case of Middle Eastern countries.

Further, other alternatives of hybridization and low-grade heat utilization can be incorporated to bring down the capital and production costs of desalinated water since these options are suitable for large-scale applications. Hybridization of two different processes, as discussed in Section 4.2, improves the performance of both systems. Membrane systems are reported to perform better when they are combined with thermal systems and vice versa. Further, if the hybrid processes are powered by renewable energy sources, the overall system economies can be improved in a more sustainable pathway. For example, a MSF process of capacity 528,000 m^3/day produces desalinated water at a cost of \$0.42/m^3. The desalination cost can be reduced by 15% if the MSF unit is combined with a RO unit for same production capacity [98]. In dual-purpose plants (cogeneration), the desalinated water cost can be minimal or as low as \$0.08/m^3 (see Table 12). A hybrid NF–RO–MSF-crystallization unit can produce desalinated water at a cost as low as \$0.30/m^3 [114]. Similarly, pre-treated wastewater can be recovered using membrane processes for reuse at costs much lower than conventional seawater desalination. The recovered water can be recommended for other potable uses except drinking, cooking and personal hygiene needs.

7. Conclusions

Several alternatives to address the global concern of water and energy sustainability are discussed on the basis of availability, applicability and cost factors. These alternatives include utilizing renewable energy sources, developing new hybrid processes, inventing low-cost, low-energy desalination processes to utilize low-grade or waste heat sources and finally water reuse.

A shift in the dependence of desalination processes on to the renewable sources from non-renewable sources has been discussed with practical applications. The selection of the appropriate renewable energy source powered desalination technology depends on variety of factors such as plant size, feed water salinity, remoteness, availability of grid electricity, technical infrastructure and the type and potential of the local renewable energy resource. Among the possible combinations of desalination and renewable energy technologies, solar and wind energy sources have been greatly exploited and found to be more promising in terms of economic and technological feasibility. However, the applicability depends strongly on the local availability of these resources and the quality of feed source to be desalinated. Other renewable energy sources such as geothermal and wave energy are to be studied in detail for practical and stand-alone applications as they have great potential to replace fossil fuels in the near future. Geothermal source, especially, is promising because it is continuous and predictable energy source with lower desalination costs. Finally, high costs for desalination can be compensated by some incentives offered by renewable energy sources such as reliable energy production over the entire life span, lower operating and maintenance costs and environmental-benign process.

Process hybridization is another sustainable pathway to improve the process economics and energy requirements of dual technologies that are involved in hybridization. This eliminates the need for large capital costs as two different processes can be built on the same platform and common design can be implemented. Duplication of equipment, raw materials and facilities can be avoided. Furthermore, if hybrid processes can utilize renewable energy sources, they not only improve the process economics but also free the desalination processes from fossil fuel dependence and reduce environmental emissions.

Another green approach is to utilize the low-grade reject heat sources or process waste heat sources which are often available, free of cost. Depending on the nature and availability of the low-grade heat source, the applications can be domestic, local and regional. Examples of low-grade heat sources include: domestic air-conditioning systems, geothermal sources and low-grade solar collectors. Thermodynamic efficiency of low-temperature desalination with low-cost materials can bring down the desalination cost to a minimum.

Finally, water reuse option to recover pre-treated wastewater can be achieved with low pressure membranes involving minimum production costs. These systems, in most cases, can be combined with the process whose effluent is the feed source. The recovered water can be used for non-potable uses while precious desalinated water can be used for better purposes. By doing this, the stress on natural water and energy sources can be reduced.

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